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Parton distribution of proton in a simple statistical model

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Abstract

Taking proton as an ensemble of quark–gluon Fock states and using the principle of detailed balance, we construct a simple statistical model for parton distribution of proton. The recent observed Bjorken- x dependent light flavor sea quark asymmetry $\bar{d}(x) - \bar{u}(x)$ can be well reproduced by Monte Carlo simulation as a pure statistical effect.

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Proton is the simplest system in which the three colors of QCD neutralize into a colorless object, but its internal quark–gluon structure is still not well understood. The complication comes from the presence of sea quarks in the proton. In all global analyses of parton distribution in nucleons before 1990, a symmetric light-quark (\bar{u} , \bar{d}) sea was assumed, based on the usual assumption that the sea of quark–antiquark pairs is produced perturbatively from gluon splitting [1]. However, a surprisingly large asymmetry between the \bar{u} and \bar{d} sea quark distributions in the proton has been observed in recent deep inelastic scattering [2,3] and Drell–Yan experiments [4–6].

There have been many theoretical attempts [7–11] trying to find the origins for this asymmetry. It is believed [1,6] that the asymmetry cannot be produced

from perturbative QCD and mesonic degrees of freedom play an important role for the effect.

In this Letter we follow a new idea [12] for the origin of the light flavor sea quark asymmetry to reproduce the recent observed $\bar{d}(x) - \bar{u}(x)$ distribution [6] with a simple statistical model. The basic idea in Ref. [12] is rather simple: while sea quark–antiquark pairs are produced flavor blindly by gluon splitting, \bar{u} quarks have larger probability to annihilate than \bar{d} quarks due to the fact that there are more u quarks than d quarks in the proton, which hence causes the asymmetry. Taking proton as an ensemble of quark–gluon Fock states [13,14] and using the principle of detailed balance for transitions between various Fock states through creation or annihilation of partons, the probabilities $\rho_{i,j,k}$ of finding the quark–gluon Fock states $|\{uud\}\{i,j,k\}\rangle$ have been obtained and given in Table 2 of Ref. [12], with i, j, k the number of $\bar{u}\bar{u}$ pairs, the number of $\bar{d}d$ pairs, the number of gluons, respectively. With the density matrix $\rho_{i,j,k}$ for

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the quark–gluon Fock states $|\{uud\}\{i, j, k\}\rangle$, the sea-quark flavor asymmetry was calculated as $\bar{d} - \bar{u} \approx 0.124$, which is in surprisingly agreement with the experimental data $\bar{d} - \bar{u} = 0.118 \pm 0.012$. Encouraged by this success, here we want to extend the model to calculate the Bjorken- x distribution of partons to study the x -dependence of the flavor asymmetry in the nucleon sea, $\bar{d}(x) - \bar{u}(x)$, which has recently been well measured by the FNAL E866/NuSea Collaboration [5,6].

For a quark–gluon Fock state $|\{uud\}\{i, j, k\}\rangle$, the total number of partons is $n = 3 + 2i + 2j + k$. If the n partons were free particles without mutual interactions, their momentum distribution $d\rho_n^F(p_1, \dots, p_n)$ would simply follow the n -body phase space, i.e.,

$$\begin{aligned} d\rho_n^F(p_1, \dots, p_n) &= d\Phi_n(P; p_1, \dots, p_n) \\ &= \delta^4\left(P - \sum_{i=1}^n p_i\right) \prod_{i=1}^n \frac{d^3 p_i}{(2\pi)^3 2E_i} \end{aligned} \quad (1)$$

with P the 4-momentum of the proton, p_1, \dots, p_n the 4-momenta of n partons. If we ignore the mass of partons, then $E_i \equiv \sqrt{\vec{p}_i^2 + m_i^2} = |\vec{p}_i| \equiv p_i$ and we have

$$\begin{aligned} d\rho_n^F(p_1, \dots, p_n) &= \delta^4\left(P - \sum_{i=1}^n p_i\right) \prod_{i=1}^n \frac{P_i dP_i d\Omega_i}{2(2\pi)^3} \\ &= \delta^4\left(P - \sum_{i=1}^n p_i\right) \prod_{i=1}^n \frac{E_i dE_i d\Omega_i}{2(2\pi)^3}. \end{aligned} \quad (2)$$

However, we know that partons are not free particles and are confined in the proton. In potential picture, partons are almost free only near the center of the proton and their momenta decrease when moving away from the center. Partons with smaller momenta at the center stay longer close to the center while partons with larger momenta at the center stay shorter around the center. So compared with total free particles, partons in the proton should have larger probability for smaller momenta. In this Letter we assume the n -parton momentum distribution $d\rho_n(p_1, \dots, p_n)$ to be

$$\begin{aligned} d\rho_n(p_1, \dots, p_n) &= \frac{1}{\prod_{i=1}^n P_i} d\Phi_n(P; p_1, \dots, p_n) \end{aligned}$$

$$\begin{aligned} &= \delta^4\left(P - \sum_{i=1}^n p_i\right) \prod_{i=1}^n \frac{dP_i d\Omega_i}{2(2\pi)^3} \\ &= \delta^4\left(P - \sum_{i=1}^n p_i\right) \prod_{i=1}^n \frac{dE_i d\Omega_i}{2(2\pi)^3}. \end{aligned} \quad (3)$$

This is equivalent to assuming equal probability for any energy configuration (E_1, \dots, E_n) of n partons in the proton.

With the n -parton momentum distribution $d\rho_n(p_1, \dots, p_n)$ and taking the light front formula for the Bjorken- x

$$x = \frac{E_{\text{parton}} - p_{z, \text{parton}}}{M_{\text{proton}}}, \quad (4)$$

we can easily get the x -distribution of partons, $\rho_n(x)$, for an n -parton Fock state of the proton by using a simple Monte Carlo simulation with a Monte Carlo event generator program called GENEV from the CERN computer program library (CERNLIB). The $\rho_n(x)$ is normalized as $\int_0^1 dx \rho_n(x) = 1$.

For a n -parton Fock state $|\{uud\}\{i, j, k\}\rangle$, the total number of partons is n including u, d, \bar{u}, \bar{d} and g with parton number of $2 + i, 1 + j, i, j$ and k , respectively. Then the x -distribution for each kind of partons, $u_{i,j,k}(x)$, $d_{i,j,k}(x)$, $\bar{u}_{i,j,k}(x)$, $\bar{d}_{i,j,k}(x)$ and $g_{i,j,k}(x)$, are

$$u_{i,j,k}(x) = \rho_n(x)(2 + i), \quad (5)$$

$$d_{i,j,k}(x) = \rho_n(x)(1 + j), \quad (6)$$

$$\bar{u}_{i,j,k}(x) = \rho_n(x)i, \quad (7)$$

$$\bar{d}_{i,j,k}(x) = \rho_n(x)j, \quad (8)$$

$$g_{i,j,k}(x) = \rho_n(x)k. \quad (9)$$

Summing up parton x -distribution of all possible Fock states $|\{uud\}\{i, j, k\}\rangle$ according to their weights $(\rho_{i,j,k})$ in Table 2 of Ref. [12] to get the parton x -distribution of proton, we have

$$u(x) = \sum_{i,j,k} \rho_{i,j,k} u_{i,j,k}(x), \quad (10)$$

$$d(x) = \sum_{i,j,k} \rho_{i,j,k} d_{i,j,k}(x), \quad (11)$$

$$\bar{u}(x) = \sum_{i,j,k} \rho_{i,j,k} \bar{u}_{i,j,k}(x), \quad (12)$$

$$\bar{d}(x) = \sum_{i,j,k} \rho_{i,j,k} \bar{d}_{i,j,k}(x), \quad (13)$$

$$g(x) = \sum_{i,j,k} \rho_{i,j,k} g_{i,j,k}(x), \quad (14)$$

which satisfy normalization condition

$$\int_0^1 x [u(x) + d(x) + \bar{u}(x) + \bar{d}(x) + g(x)] dx = 1. \quad (15)$$

Our $u(x)$ and $d(x)$ include both valence and intrinsic sea quarks which are identical and not distinguishable in our approach. The x -distribution of valence quarks (u_v, d_v) can be easily obtained as

$$u_v(x) = u(x) - \bar{u}(x), \quad (16)$$

$$d_v(x) = d(x) - \bar{d}(x). \quad (17)$$

In addition, we have

$$\begin{aligned} \bar{n} &= \int_0^1 [u(x) + d(x) + \bar{u}(x) + \bar{d}(x) + g(x)] dx \\ &= 5.57, \end{aligned} \quad (18)$$

$$\bar{E} = \frac{M_{\text{proton}}}{\bar{n}} = \frac{0.938 \text{ GeV}}{5.57} = 0.168 \text{ GeV}, \quad (19)$$

where \bar{n} is the average number of partons in proton and \bar{E} is the average energy of partons in proton.

From above equations we get the parton x -distribution densities $f(x, \mu_0^2)$ ($f = u, d, \bar{u}, \bar{d}, g$) as shown in Fig. 1 with the scale $\mu_0 \approx \bar{E} = 0.168 \text{ GeV}$.

The corresponding momentum distribution, $xf(x, \mu_0^2)$, is shown in Fig. 2. As a comparison, the $xf(x, Q^2)$ distribution of GRV [15] at some higher Q^2 is shown in Fig. 3. It will be interesting to check whether with some QCD evolution equation our $xf(x, \mu_0^2)$ distribution could evolve into a momentum distribution $xf(x, Q^2)$ at higher Q^2 to be similar to the GRVs.

The quarks and gluons in the Fock states are the “intrinsic” partons of the proton, multi-connected non-perturbatively to the valence quarks [16]. Such partons are different from “extrinsic” partons generated from the QCD hard bremsstrahlung and gluon-splitting as part of the lepton scattering interaction. Partons measured at certain Q^2 by experiments include both “intrinsic” and “extrinsic” ones. Since “extrinsic” partons are generated flavor blindly, the light flavor sea quark asymmetry is mainly due to “intrinsic” partons and is practically Q^2 independent, although correlations between “intrinsic” and “extrinsic” partons can

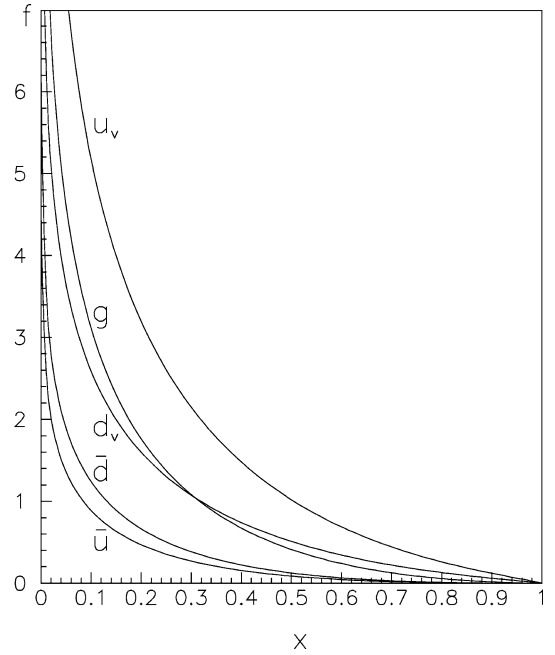


Fig. 1. The parton density f ($f = u_v, d_v, \bar{u}, \bar{d}, g$) of our model at a scale $\mu_0 \approx 0.168 \text{ GeV}$. The $f(x)$ in our model is simulated using Monte Carlo without any parameter. All we need in our model are principle of detailed balance and assumption of equal probability for every energy configuration of an n -parton Fock state.

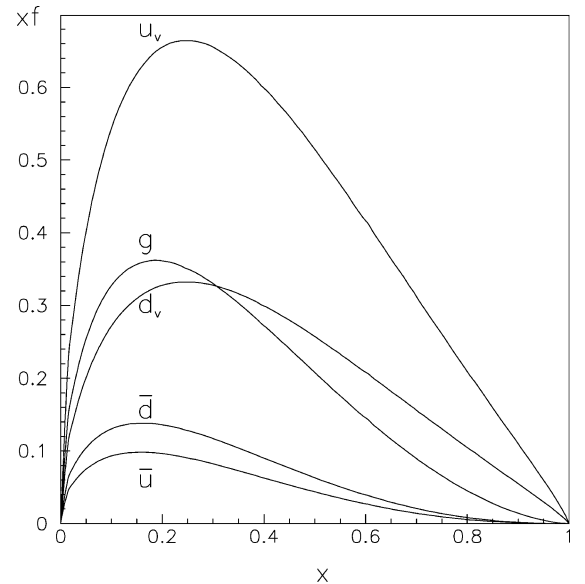


Fig. 2. The densities xf ($f = u_v, d_v, \bar{u}, \bar{d}, g$) of our model at a scale $\mu_0 \approx 0.168 \text{ GeV}$.

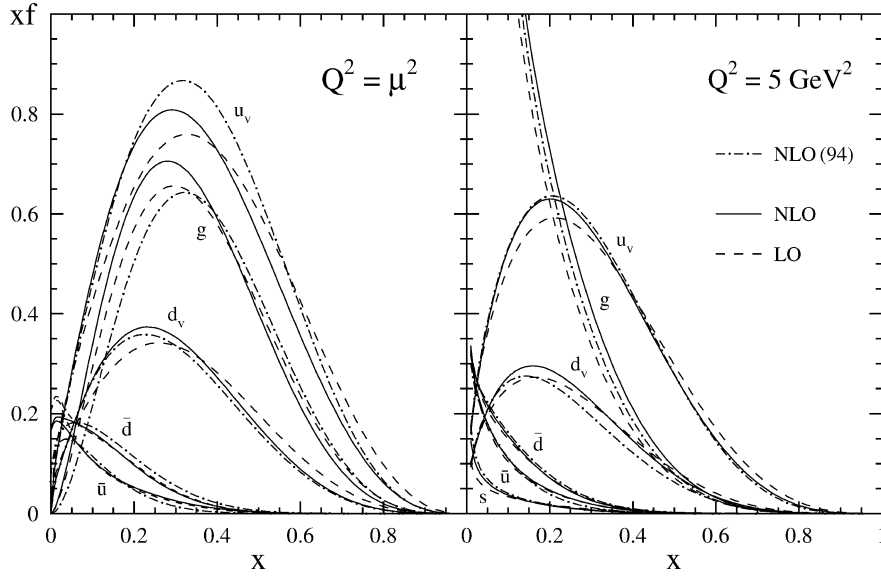


Fig. 3. For a comparison, the $xf(x)$ of GRV [15] at higher Q^2 . Left: input densities xf ($f = u_v, d_v, \bar{u}, \bar{d}, g$) at $Q^2 = \mu_{LO}^2 = 0.26 \text{ GeV}^2$ and $Q^2 = \mu_{NLO}^2 = 0.40 \text{ GeV}^2$, at which scales strange sea $s = \bar{s}$ vanishes. Right: the evolved results at $Q^2 = 5 \text{ GeV}^2$.

cause some small Q^2 dependence for the asymmetry. Experimental data at various Q^2 values also show little Q^2 dependence [1,6]. Hence we can compare our model prediction of $\bar{d}(x) - \bar{u}(x)$ at the low scale μ_0 directly with experimental data at higher scales, as shown in Fig. 4. Our prediction is in good agreement with recent experiment data of FNAL E866/NuSea [6] at $Q^2 = 54 \text{ GeV}^2$ and HERMES [3] at $\langle Q^2 \rangle = 2.3 \text{ GeV}^2$.

In summary, following Ref. [12] we take proton as an ensemble of quark-gluon Fock state, i.e., $|p\rangle = \sum_{i,j,k} c_{i,j,k} |\{uud\}\{i,j,k\}\rangle$, with $\rho_{i,j,k} \equiv |c_{i,j,k}|^2$ determined by the principle of detailed balance. By further assuming equal probability for any energy configuration (E_1, \dots, E_n) of n -parton Fock state in the proton, we get parton x -distribution functions at a scale of $\mu_0 \approx \bar{E} = 0.168 \text{ GeV}$ with a Monte Carlo simulation of a simple statistical model. The corresponding light flavor sea quark asymmetry $\bar{d}(x) - \bar{u}(x)$ reproduces the recent experiment data quite well. This is a further support of the new origin of the light flavor sea quark asymmetry as a pure statistical effect due to the fact that there are more u -quarks than d -quarks in the proton.

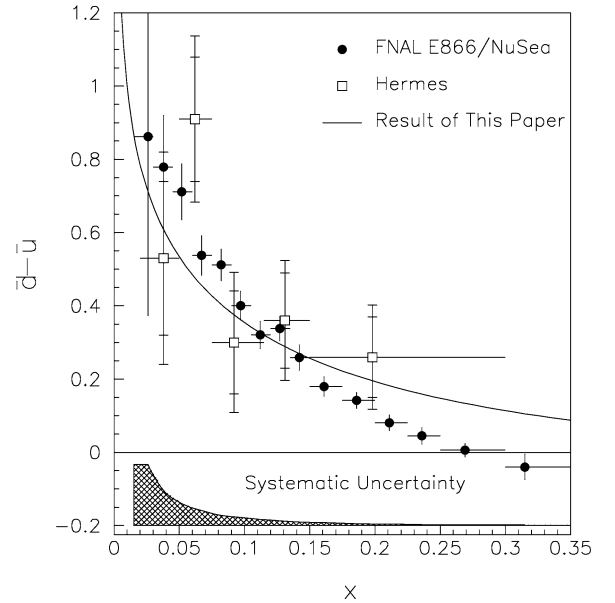


Fig. 4. Comparison of measured $\bar{d}(x) - \bar{u}(x)$ to prediction of our model at scale $\mu_0 \approx 0.168 \text{ GeV}$. The FNAL E866/NuSea results, scaled to fixed $Q^2 = 54 \text{ GeV}^2$, are shown as the circles; HERMES results of $\langle Q^2 \rangle = 2.3 \text{ GeV}^2$ are shown as squares.

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